The HERMES dual-radiator RICH detector

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The HERMES experiment emphasizes measurements of semi-inclusive deep-inelastic scattering. Most of the hadrons produced lie between 2 and 10 GeV, a region in which it had not previously been feasible to separate pions, kaons, and protons with standard particle identification (PID) techniques. The recent development of new clear, large, homogeneous and hydrophobic silica aerogel material with a low index of refraction offered the means to apply RICH PID techniques to this difficult momentum region. The HERMES instrument uses two radiators, C_4F_{10}, a heavy fluorocarbon gas, and a wall of silica aerogel tiles. A lightweight spherical mirror constructed using a newly perfected technique to make resin-coated carbon-fiber surfaces of optical quality provides optical focusing on a photon detector consisting of 1934 photomultiplier tubes (PMT) for each detector half. The PMT array is held in a soft steel matrix to provide shielding against the residual field of the main spectrometer magnet. Ring reconstruction is accomplished with pattern recognition techniques based on a combination of inverse and direct ray tracing.

1. Introduction

The HERMES experiment[1] is a study of the spin structure of the nucleon which emphasizes unambiguous measurement of pion, kaon, and proton semi-inclusive spin asymmetries in deep-inelastic scattering (DIS). These asymmetries provide information on the flavor dependence of polarized structure functions and the sea polarization. However, most of the hadrons produced in HERMES [2] lie between 2 and 10 GeV, a region in which it has not been feasible to separate pions, kaons, and protons with standard particle identification (PID) techniques. Ring Imaging Čerenkov (RICH) and threshold Čerenkov systems using heavy gases [3], such as C_4F_{10}, at atmospheric pressure are useful only for energies above 10 GeV since the kaon threshold for Čerenkov radiation is typically higher than 9 GeV. Because of substantial multiple scattering and bremsstrahlung, the use of a high pressure gas system is not technically feasible in HERMES. Clear liquid radiators are only useful for hadron identification below roughly 2 GeV because of their very low Čerenkov light thresholds and large chromatic dispersion.

The recent development[4,5] of new clear silica aerogel with a low index of refraction and excellent optical properties has made it possible, for the first time, to span this difficult energy region. The HERMES RICH detector combines the successful use, of clear aerogel with a heavy gas, C_4F_{10}, in a single detector. Such a configuration was first proposed for the planned LHCb experiment [6]. This dual-radiator RICH detector provides clean separation of pions, kaons, and protons over most of the kinematic acceptance of the HERMES experiment.

2. Detector design

About 95% of all hadrons detected in the HERMES experiment are found in the range of 2.0 to 15.0 GeV. This defines the momentum range over which clear particle identification should be provided. The low end of this range determines the index of refraction necessary for the aerogel. A value of n(λ=633 nm)=1.03 was chosen since it leads to a kaon threshold of 2 GeV. The Čerenkov angles produced by the combination of this aerogel and the heavy gas (C_4F_{10}) for pions, kaons and protons are plotted in figure 1 as a function of particle momentum. The corresponding threshold momenta are listed in table 1. All pion momenta within the spectrometer acceptance are above the pion threshold momentum for aerogel of 0.6 GeV, 90% of the kaon and 78% of the proton momenta are above the kaon threshold of 2.0 GeV.

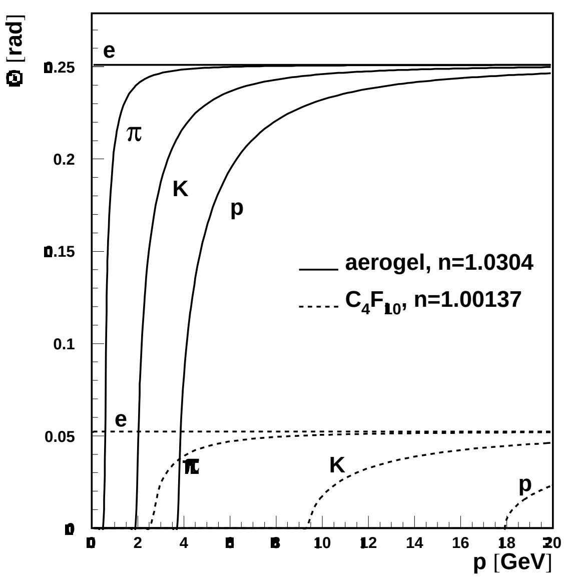

Figure 1. The Čerenkov angle θ versus hadron momentum for the aerogel and C_4F_{10} gas radiators.

Studies of the properties of aerogel were carried out with a CERN test beam, and the optical properties of a sample of 200 tiles were studied in detail [7–10]. The optimum thickness for the aerogel radiator was determined to be about 5 cm. The single photo-electron resolution required was fixed by the requirement that, at 15 GeV, misidentification be less than 1% for equal fluxes of pions and kaons. For projected aerogel yields of $N \approx 12$, this resolution is about 7 mr. Consequently, 3/4 inch photomultiplier tubes were chosen for the the photon detector, giving a pixel size of 23.3 mm. Monte Carlo simulations gave single photon resolution for this geometry of 5-6 mr.

	aerogel	C_4F_{10}
n	1.0304	1.00137
$\beta_t\gamma_t$	4.05	19.10
π	0.6 GeV	2.7 GeV
K	2.0 GeV	9.4 GeV
p	3.8 GeV	17.9 GeV

Table 1
Čerenkov light thresholds for pions, kaons and protons. The index of refraction n is given at 633 nm, $\beta_t = 1/n$ is the threshold velocity and $\gamma_t = 1/\sqrt{1-\beta_t^2}$.

The geometry which was adopted for the Čerenkov radiators and ring imaging systems is shown in figure 2. Shown is one half of the the RICH system which consists of identical units placed above and below the median plane of the HERMES spectrometer. The body of the counter is constructed of aluminum, with entrance and exit windows made of 1 mm thick aluminum. The volume of each half is approximately 4000 l. The size of the entrance window is 187.7 cm by 46.4 cm and the exit window 257.0 cm by 59.0 cm.

The aerogel radiator is an assembly of tiles configured to fill the entrance of the detector with an aerogel thickness of 5.5 cm. The aerogel tiles are stacked in 5 layers, with 5 horizontal rows, and 17 vertical columns as required to span the spectrometer acceptance. Black plastic spacers of appropriate thicknesses between the aluminum frame and the tiles prevent them from shifting while the radiator is moved. The unoccupied volume of the detector behind the aerogel is filled with the gas radiator, C_4F_{10}. A spherical mirror array located at the rear of the radiator box images the Čerenkov light cones onto a focal surface located above (below) the active volume.

The radius of curvature of the mirror array is 2.20 m. It was chosen to give a focal surface location in the accessible region above (below) the forward region of the radiator boxes and to provide a detector plane of tractable dimensions. The optical axis of the array, the perpendicular to the mirror surface at the center of the array, is inclined at an angle of 26 degrees to the horizon. Both the

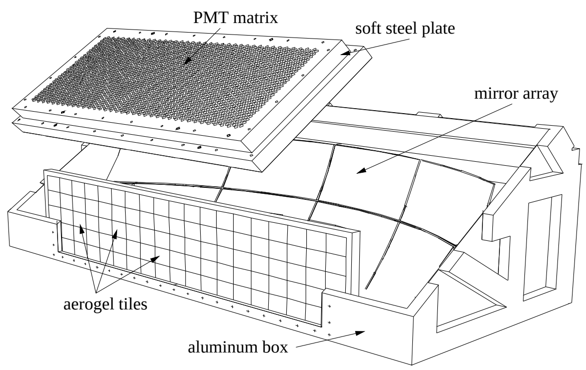

Figure 2. A cutaway schematic view of the (top) RICH counter.

mirrors and the mounting frame were fabricated by Composite Mirror Applications (Tucson, Arizona, USA)[1]. The backing of the segments is fabricated from a graphite fiber composite [11] and the total thickness of the array is less than 1% of a radiation length.

The photon detector is located outside of the mirror optical axis with its axis inclined at an angle of 40 degrees to the horizon so as to intercept the mirror surface at a distance of 90 cm. It consists of a close packed matrix of 1934 Phillips XP1911/uv green enhanced photomultipliers. This configuration was first used by the experiment E781-SELEX at FNAL [12]. The elementary cell of the array is a hexagon with the photomultiplier at the center and a light-gathering which is used to increase the photon light collection efficiency by reducing the dead space between the photocathodes. A soft steel matrix plate and wrappings of 100 μm μ-metal provide magnetic shielding.

The readout of the photon detector is performed by the commercial LeCroy PCOS4 acquisition system, upgraded for the HERMES application. Each detector half is read out by a set of 8 symmetric backplane sections, each housing 15 or 16 PCOS4 cards. Each card in turn processes signals from 16 PMTs. Only digital information - when the pulse exceeds the threshold of 0.1 photoelectrons - is recorded. The system is characterised by high input sensitivity (the threshold is 3000 electrons) and high amplification (-4.3 μV per electron). The PCOS4 system generates a data stream on an event-by-event basis. The RICH data consists of a RICH hit table for each detector half, where a PMT 'hit' simply refers to a PMT that fired during the event time window. A RICH mapping file is used to link the data channel numbers computed in the decoding process to the PMT location in the detector matrix. This information can then be used to generate the spatial hit coordinates and the hit pattern in the focal plane.

3. Ring/Angle reconstruction

Since the sensitive face of the flat photon detector does not conform to the true mirror focal surface, the detected 'rings' are not circles, but in general asymmetrically distorted ellipses. Figure 3 shows the offline RICH event display for a three-track event that illustrates several typical features of HERMES RICH events. The event shown has a 14.6 GeV electron[2] and a 1.5 GeV pion in the lower half, and a 5.5 GeV kaon in the upper half of the detector. The solid black points mark the PMT hits, while the markers in the ring centers indicate the virtual track hit points, i.e. the points where the particle tracks would intersect the photon detector if they were imaged by the mirror. The solid lines are spline fits to a few simulated photon hits. They indicate where, based on the track parameters and the particle type, hits could be expected for this event. The electron track is easily identifiable as the only one with a gas ring; a comparison to figure 1 shows that only for the electron a gas ring is expected. The momentum of the pion is below the pion gas threshold and thus it only exhibits an aerogel ring. However, the particle clearly must be a pion, because the particle momentum is below the aerogel threshold for kaons. The kaon in the top detector has a well defined aerogel ring,

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[2] Electrons and positrons are identified by a combination of calorimeter, preshower and TRD with an average efficiency of 99% and a hadron contamination below 1% [1].

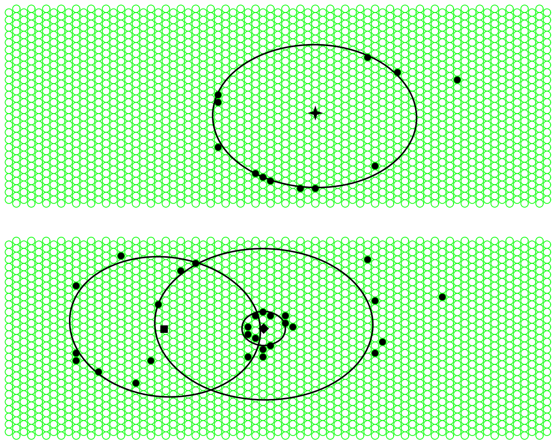

Figure 3. HERMES RICH event display for an event with a 14.6 GeV electron (right) and a 1.5 GeV π^- (left) in the lower half and a 5.5 GeV K^- in the upper half. See text for detailed description.

but no gas ring - as is expected for a kaon at 5.5 GeV.

The analysis of the hit patterns is intrinsically complex since the non-linearities of the imaging system distort the simple ring structure of the emitted light. The influence of the imaging system can be removed by *inverse ray tracing* (IRT) [6,13]. In this method the Čerenkov angle corresponding to each PMT hit is reconstructed from the track parameters and the position of the PMT. For each track it is assumed that the hit could be coming from the aerogel or the gas, and the emission vertex is estimated accordingly. For each radiator hypothesis, the emission angle is then reconstructed. Due to the very different index of refraction, it is rarely a problem to distinguish which radiator hypothesis is correct. For each track the distribution of angles for hits in an angular zone corresponding to each particle hypothesis(π,K,and p) is reconstructed. From these distributions the likelihoods are then calculated for each possibility. The likelihoods for the two radiators, aerogel and gas, are combined in an overall likelihood by multiplication. The particle is assigned the type with the highest likelihood. For a detailed discussion of the IRT method as well as a second reconstruction method, direct ray tracing, the reader is referred to the contribution by Hommez [14].

4. Performance and calibration

The detector performance ultimately is measured by how well the various particle types are identified. For a given particle identification algorithm this performance is determined by the number of detected gas and aerogel photons, as well as the single photon resolution. Complications arise from overlapping rings and background hits. The number of aerogel photons detected strongly depends on how much the track is affected by acceptance effects from the finite size of the mirror array and the tile structure of the aerogel radiator. For ideal tracks that do not suffer from acceptance or overlap effects, the asymptotic yields for particles with $\beta \approx 1$ are 10 aerogel hits and 12 gas hits. Because on the average the number of hits per phototube for the gas rings approaches 2, the gas hits are much fewer than the number of photoelectrons.

In addition to the trackless rings, there are several sources of background photons that do not necessarily result in ring structures. These include Rayleigh scattered photons, Čerenkov photons produced in the lucite window, proton beam correlated background showers that hit the PMT matrix directly and scintillation in the gas. The electronic and PMT noise in the detector is a very small effect, amounting to only about 1 fired PMT every 5 events.

Figure 4 shows the reconstructed average aerogel angle for pions. The data were fit with a theoretical curve with the aerogel index of refraction as the only free parameter. The resulting curve and index of refraction (n=1.0304) are in excellent agreement with the theoretical expectation and the optically measured index of refraction. The experimental value of the total angular resolution for single photons was determined from

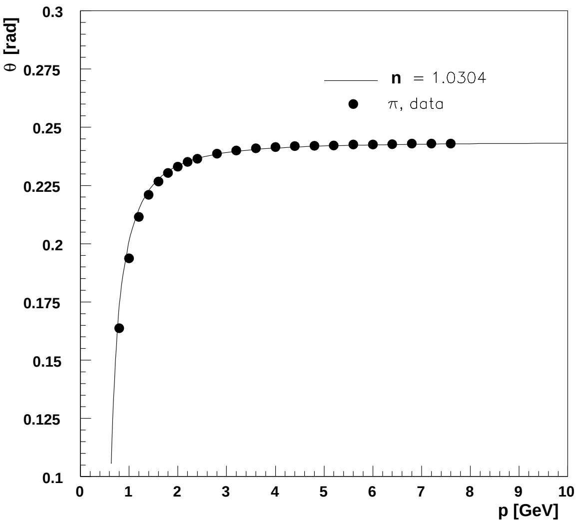

Figure 4. Reconstructed average aerogel angle versus particle momentum for pions. The solid line represents a fit with n=1.0304.

high energy lepton tracks to be 7.6 mr for aerogel and 7.5 mr for C_4F_{10}, compared to a design goal of 7 mr.

It is not possible to use another detector to create clean hadron samples to study the detector performance. However, it is possible to use decaying particles for the same purpose. Samples of ρ, ϕ and K_s mesons as well as Λ hyperons were used to determine the identification efficiencies for pions, kaons and protons. The quantity, P_i^j, ie. the probability for identifying particle type i as type j provides the best measure of detector performance. For kaons in the range of 3-6 GeV, $P_K^K \approx 90-95\%$ for kaons from ϕ decay. In this same momentum range, for isolated tracks, $P_\pi^\pi > 95\%$.

5. Summary

The HERMES dual-radiator RICH has been in operation for 3 years. It provides reliable hadron particle identification over the momentum range 2-15 GeV/c. To date, based on monitoring of detector yields and Cerenkov angles as a function of particle momentum, there is no evidence for measurable degradation in performance.

Acknowledgements

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